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Research on ReBCO and MgB2 wires and cables at the University of Twente

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14. ABSTRACT

This is a report of the effect of transverse load and combined tensile/torsion stress on the current-carrying capability of REBCO (particularly Superpower SCS4050 tape) by experiments at 77K, and including detailed modeling work on the mechanical behaviour and its influence on critical properties. The predictive model is verified by experiments. Four cable types (CORC, stacked tape, Roebel, CICC) were subjected to magnetic fields and other tests and various measurements taken. The report includes mechanical performance of cables in strain, AC loss of signals, transport current loss, intra-strand resistance and current transfer length in multifilamentary Conductors, characterization of MgB2 wires, and development MgB2 high current cabled conductor for fusion.

15. SUBJECT TERMS

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Content

RESEARCH AND DEVELOPMENT
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1. Summary

The effect of transverse load and combined controlled tensile and torsion stress on the degradation of the current carrying capability of REBCO, in particular Superpower SCS4050 tape, was studied extensively by experimental way at 77 K. Besides that, a detailed modeling work on the mechanical behaviour and it's influence on the critical properties including the influence of the manufacture process, the coil winding, the cool-down and the electromagnetic forces during operation of the tapes is completed. The predictive potential of the model has been verified by the experiments. To our knowledge, this model is the most extensive build so far and will be used for evaluation and improvement of conductor design, manufacture and operation.

Four cable types were subjected to transverse applied alternating magnetic fields, CORC manufactured by Advanced Conductor Technologies and so called stacked tape conductors assembled at CRPP Villigen (CH), Roebel type cable produced at KIT, Karlsruhe, Germany, and a full-size proto-type CICC assembled at ENEA, Frascati, Italy. In addition inter-tape contact resistances were measured under applied transverse stress. This is the first extensive AC loss study on a variety of REBCO cabled conductors, the effect of adding copper stabilizer and twisting have been evaluated.

Critical current measurements have been performed on Roebel and CORC prototype cables. The impregnated Roebel cable was subjected to transverse stress in order to evaluate it's ability to transverse load, the CORC cable was only tested on critical current under applied magnet field. The next step is to do transport current experiments combined with stability studies on CORC and Roebel type of cables in the facility at the University of Twente in collaboration with Advanced Conductor Technologies, KIT and CERN, Switzerland.

The intra-strand resistance and current transfer length of multi-filamentary NbTi, Nb_3Sn, MgB_2, BSSCO and REBCO superconductors has been measured with a direct four-probe voltage-current method at various temperatures. With FEM simulations, the filament-to-matrix contact resistance and effective transverse resistivity are derived from the intra-strand resistance measurements. The effective transverse resistivity values are verified with those analytically derived from AC coupling loss measurements in transverse applied field.
Intra-wire resistance and AC loss of two MgB_2 wires with filaments surrounded by Nb barriers have been measured and analyzed. Relatively high values of filament-to-matrix contact resistivity are found for the MgB2 wires, being 2 or 3 orders higher than commonly found for NbTi or Nb_3Sn wires. Cold high-pressure densification (CHPD) has been applied on the two MgB2 wires to investigate its impacts on the intra-wire resistance, AC loss and axial strain.

A consortium is formed with University of Twente (Netherlands), Hypertech Inc., Columbus, OH, (USA) Ohio State University, Columbus, OH (USA), CAS ASIPP Hefei (China) and Institute for Plasma Research BHAT, Gandhinagar (India) and the US Air Force Research Laboratory, Wright Patterson AFB, OH (USA) to design, manufacture and test a full-size 50 kA class MgB_2 cabled conductor as a prototype for application in the Poloidal Field Magnets of a fusion reactor.

2. Mechanical performance of HTS tapes and cables

For high current superconductors in high magnet fields with currents in the order of 50 kA, single ReBCO coated conductors must be assembled in a cable. The geometry of such a cable is mostly such that combined torsion, axial and transverse loading states are anticipated in the tapes and tape joints. The resulting strain distribution, caused by different thermal contraction and electromagnetic forces, will affect the critical current of the tapes. Tape performance when subjected to torsion, tensile and transverse loading is the key to understand limitations for the composite cable performance. The individual tape material components can be deformed, not only elastically but also plastically under these loads. A set of experimental setups, as well as a convenient and accurate method of stress-strain state modelling based on the Finite Element Method (FEM) have been developed. Systematic measurements on single ReBCO tapes are carried out combining axial tension and torsion as well as transverse loading. Then the behavior of a single tape subjected to the various applied loads is simulated in the model. This paper presents the results of experimental tests and detailed FE modeling of the 3D stress-strain state in a single REBCO tape under different loads, taking into account the temperature dependence and the elastic-plastic properties of the tape materials, starting from the initial tape processing conditions during its manufacture up to magnet operating conditions. Furthermore a comparison of the simulations with experiments is presented with special attention for the critical force, the threshold where the tape performance becomes irreversibly degraded. We verified the influence of tape surface profile non-uniformity and copper stabilizer thickness on the critical force. The FE models appear to describe the tape experiments adequately and can thus be used as a solid basis for optimization of various cabling concepts. The detailed modeling of the mechanical behavior including the manufacture process of the tapes is completed and the results of modeling and experiments are published in a journal paper [S-3]. The results have already been presented and discussed at many international meetings and conferences [O-1, O-2, O-3, O-4, O-5, O-6, O-8, O-9, O-10, O-11, O-13, O-16, O-18, O-19, O-23, O-24].

The new FE models for high temperature REBCO superconducting tape subjected to tensile, a combination of tensile and torsional and transvers loads were presented in this paper. The models allow for calculating the critical loads at which the critical current begins to degrade irreversibly. The threshold criterion of 0.45% strain in the REBCO layer as a starting point for irreversible critical current degradation is appropriate for all applied load types. For transverse load it is necessary to calculate the actual strain distribution in the REBCO layer over the contact area and integrate the associated critical current to obtain the critical force, for torsion to less extend. It is necessary to use elasto-plastic properties of materials and include modeling of the production process of the tape to achieve a good correlation with the experiments. The FE model allows understanding the mechanism of crack appearance especially for transverse load case. The critical force reduces considerable with increasing thickness of the copper layer, a factor three reduction is observed for 100 µm total copper layer thickness.

A performance improvement of electroplated copper REBCO tape under applied load may be anticipated when the dog-boning (see Figure 1) is avoided, thus creating a more uniform tape profile and more homogeneous stress distribution. Moreover, the “copper extrusion effect” (see Figure 2 and Figure 3) under transverse load causes lower critical force levels with increasing copper thickness, so a larger copper thickness on the tape does not act as a protection against mechanical load when only in transverse direction but works opposite by reducing its performance potential.

The next step is now to study cabling configurations with the model and search for optimal cable assembly configurations for manufacture and operation.

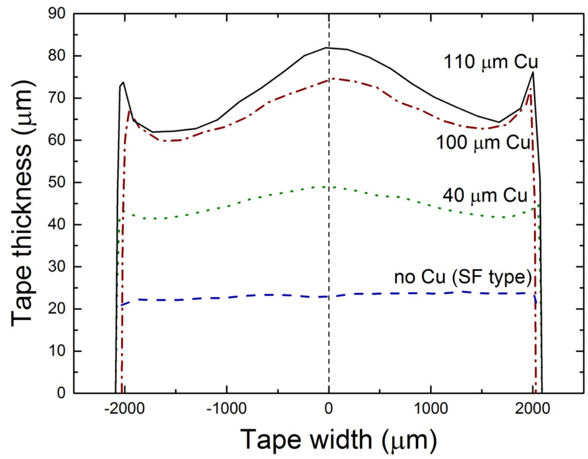

Figure 1. Average thickness profiles of different types of SuperPower® tapes, each taken from 10 cross section samples.

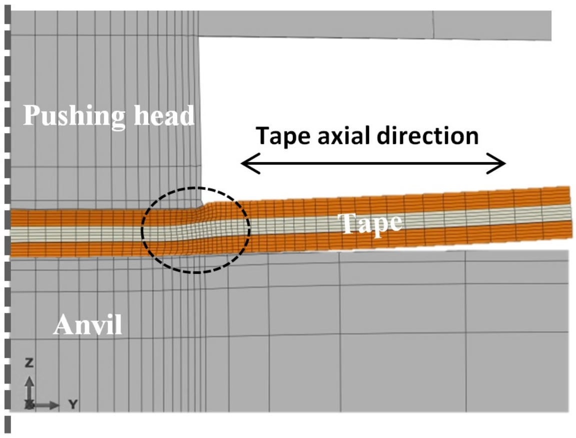

Figure 2. Calculated deformation of the tape, anvil and pushing head for SCS4050 tape with 100 µm copper under 1.3 kN of the pushing force (Cross-section view).

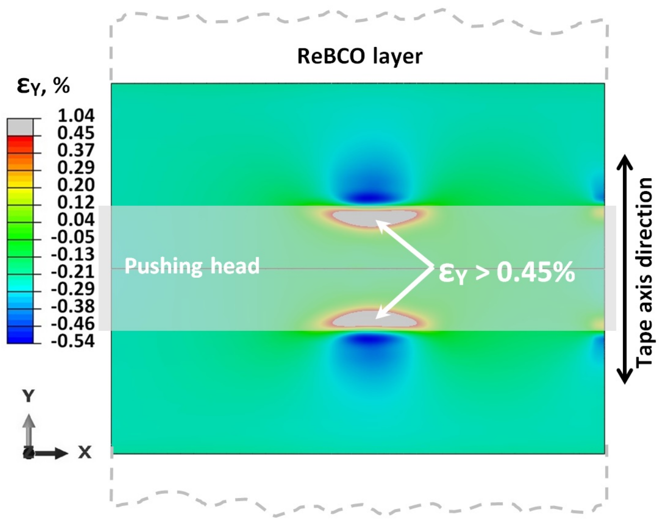

Figure 3. The longitudinal strain (along tape axis) in the ReBCO layer for SCS4050 tape with 100 µm copper for 1.3 kN pushing force obtained by FE modeling (top view). The area with the strain above 0.45% is about 0.7 mm across the tape or 17.5% of the tape width.

3. AC Loss of CORC, stacked tape, Roebel and REBCO-CICC cables

For AC application, wire twist can be introduced in cables to reduce coupling currents during magnetic field ramping but also the inter-tape contact resistance plays a crucial role. The cable types presently available and manufactured in various laboratories were subjected to transverse applied alternating magnetic fields to study the coupling and hysteresis losses with out transport current. The different cabled conductors were CORC manufactured by Advanced Conductor Technologies, CO, USA, so called stacked tape conductors assembled at CRPP Villigen, Switzerland and ENEA Frascati, Italy, and Roebel cables from KIT, Karlsruhe, Germany (see Figure 4).

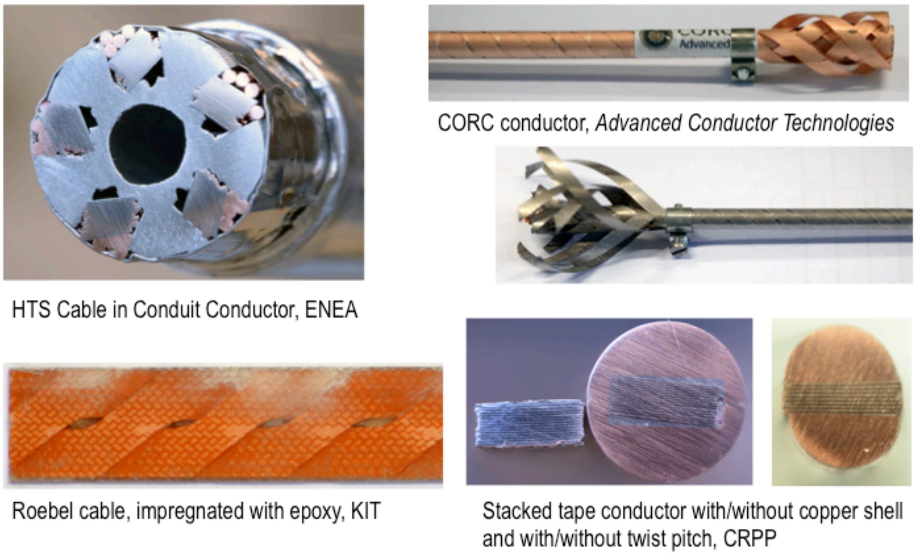

Figure 4. The different REBCO cable configurations that have been tested on AC loss.

The AC loss of eight HTS conductors manufactured according to three types of cabling methods - CORC (cable on round core), Roebel, and stacked tape, including a full-size HTS CICC (cable in conduit conductor) - were measured under the same conditions. The AC loss was measured with a calibrated gas flow calorimeter utilizing the helium boil-off method and by the magnetisation method, using pick-up coils. The measurements were done at T = 4.2 K without transport current in a sinusoidal AC magnetic field up to 0.4 T amplitude and frequencies from 5 to 55 mHz. Each conductor was measured with and without background field of 1 T. The influence of transverse load simulating the effect of Lorentz forces on CORC AC loss was studied.

As a consequence of the high aspect ratio of the HTS tapes, all non twisted conductors and the Roebel cable have high hysteresis loss in an alternating magnetic field oriented perpendicular to the wide HTS face while no coupling loss was measured for this field to sample orientation. When the field is oriented parallel to the wide side of the samples, coupling loss combined with lower hysteresis loss are observed. The highest coupling loss was seen for the non-twisted stacked tape conductor with copper shell, providing low resistive coupling [19].
When twisting is applied to a stacked tape conductor with copper shell, the coupling loss is effectively reduced at the cost of increased hysteresis loss.
The measurements show that the coupling component of the AC losses is negligible for all CORC type conductors when they are subjected to a transverse alternating magnetic field. The HTS CICC conductor clearly shows coupling loss even though it has an order of magnitude higher tape to tape Rc compared with the heat treated CORC-Sn sample. It is suggested that the low coupling loss for face on applied field direction is because the wide filaments are not fully penetrated.

Contact resistance for CORC and HTS CICC samples were measured. It was shown that contact resistances for the conductors made of copper plated HTS tapes (HTS CICC and CORC-Cu) are in the region of ~300 nΩm at T = 77.3 K and ~200 nΩm at T = 4.2 K.
We observed a step increase in contact resistance between layers with two and three tapes in the layer for CORC samples. The COCR-Sn conductor with PbSn coating in its initial conditions showed twice higher layer to layer contact resistance than the CORC-Cu conductor. The soldering between tapes of the CORC cables with PbSn coating reduced the tape to tape and layer to layer contact resistances by two orders of magnitude.
The different thermal contraction of the CORC conductor components should be considered when during conductor and magnet design

An example of the influence of twist on the coupling and hysteresis loss in stacked tape conductor manufactured by CRPP is presented in Figure 5. The AC loss is measured as a function of sinusoidal applied field with amplitude of 0.4 T with and without background field of 1 T. Another example, showing AC loss results under applied transverse pressure of CORC conductor manufactured by Advanced Conductor Technologies, is shown in Figure 6, while a summary of results for all conductors is depicted in Figure 7. An extensive overview of the results will be reported soon in a journal paper [S-4], while the results have already been reported at several international meetings or upcoming large conferences [O-7, O-13, O-17, O-20, O-25].

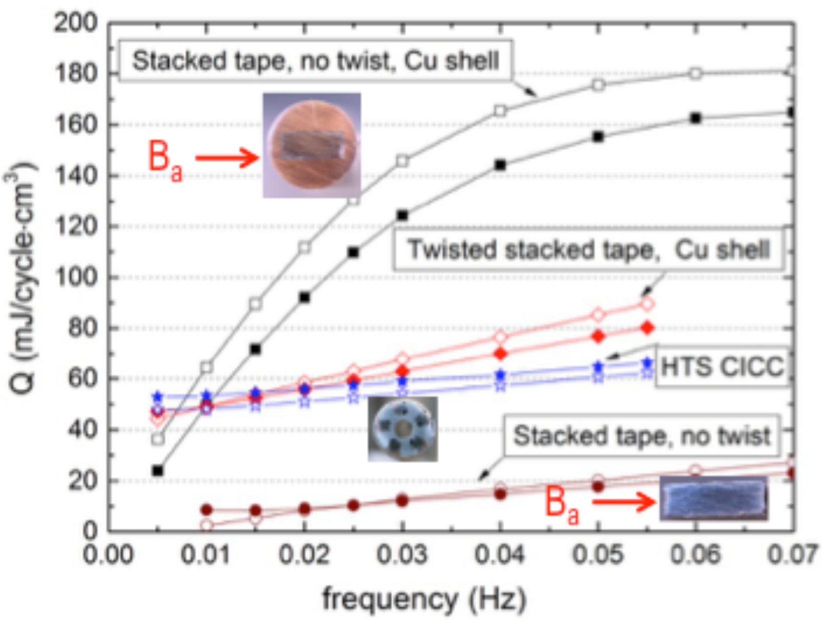

Figure 5. An example of the influence of twist in stacked tape conductor manufactured by CRPP and the REBCO-CICC made by ENEA.

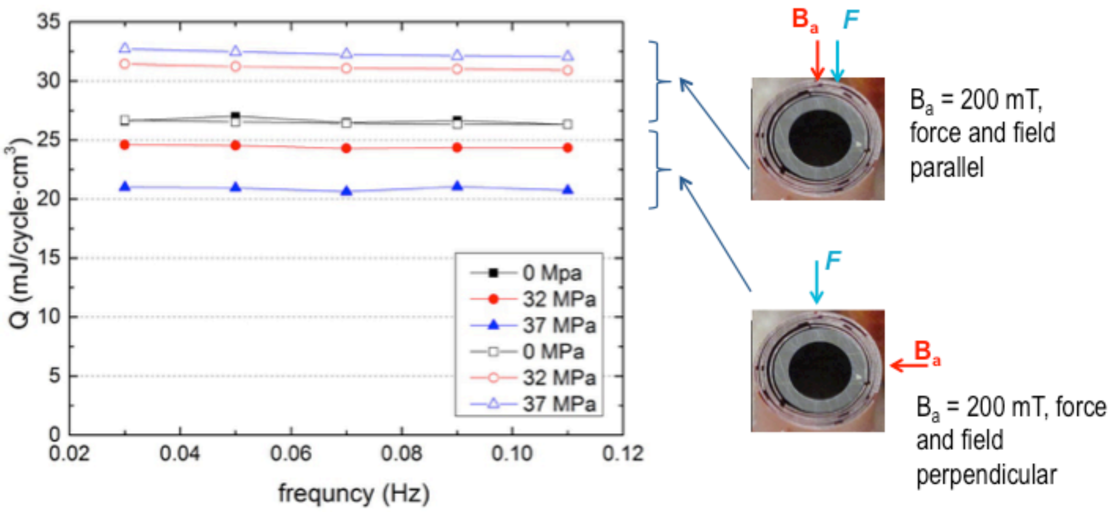

Figure 6. AC loss results under applied transverse pressure of CORC conductor manufactured by Advanced Conductor Technologies.

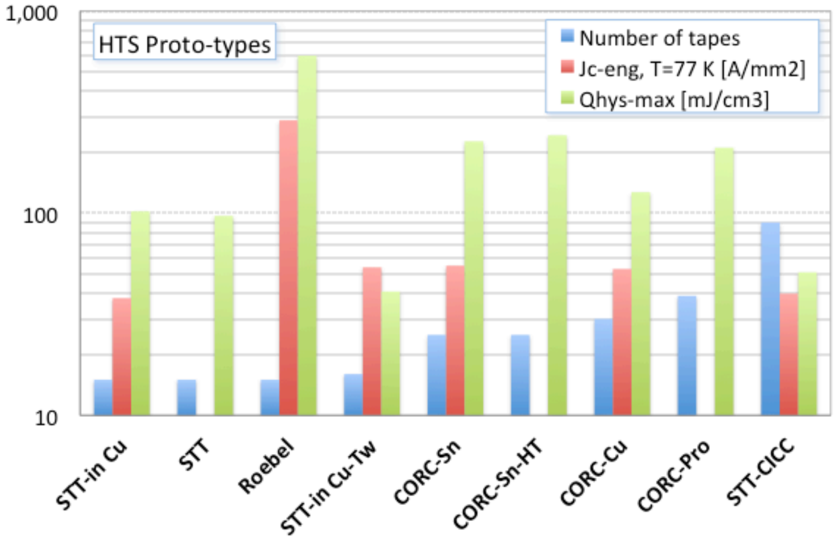

Figure 7. Summary of AC loss results, engineering critical current density and number of tapes for all conductor types tested.

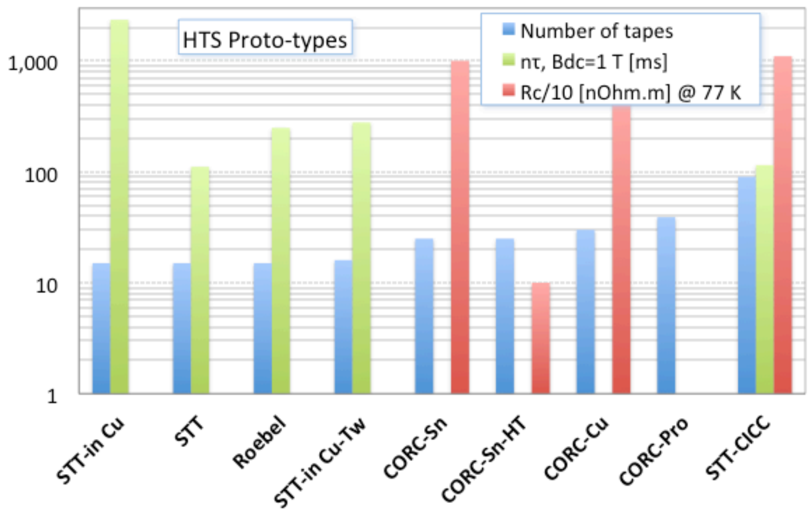

Figure 8. Summary of results, coupling loss time constants, inter-tape contact-resistance and number of tapes for conductor types tested.

4. Transport current tests on Roebel and CORC cables made with REBCO tape

The physics department of CERN is developing CORC type HTS cables for accelerator magnets and HTS high field inserts. For this purpose it is important to quantize any cable degradation due to bending. At the facility of the University of Twente an Ic test was performed on a CORC cable wound with a small bending radius [R1]. The CORC sample used for the test is comprises 38 SCS4050 REBCO tapes produced by Superpower. The tapes are helically wound in 12 layers around a central aluminium core. For the test the outer copper layers and sleeve have been removed. The outer diameter of the resulting cable configuration is now 7.5 mm. The critical current of the cable is about 7.5 kA at 10 T with an n-value of 11, tested in FRESCA (CERN). The entire sample, including the two joints is 160 cm long that fits the sample holder.

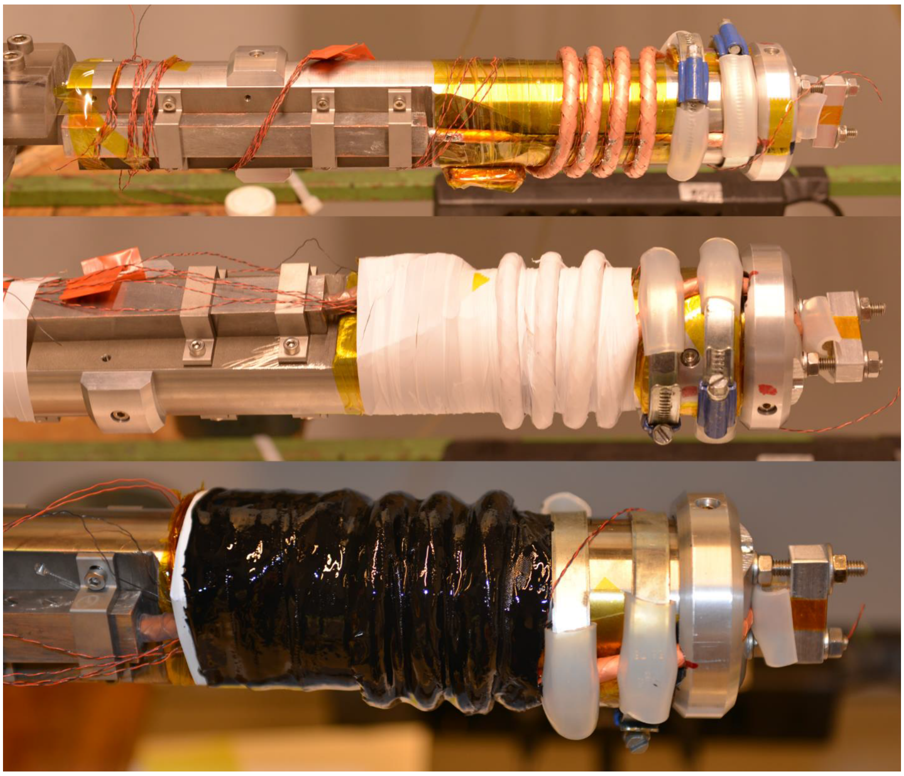

Figure 9. The sample holder including the cable, showing the different stages of the cable mounting process.

A spiraled CORC cable is tested in 0 to 10 T background field at the University of Twente. The test showed severe degradation of this cable due to winding around a sample holder with an outer diameter of 61 mm. The critical current degraded about 80% and the n-value dropped from 11 to 5. The degradation is caused by buckling of the REBCO tapes during bending of the cable (see Figure 10). The tested CORC cable is not suitable for bending radii of 30.5 mm and below. To reduce the amount of degradation CORC cables are now manufactured with narrow tapes and thinner substrate in order to be able in handling smaller bending radius.

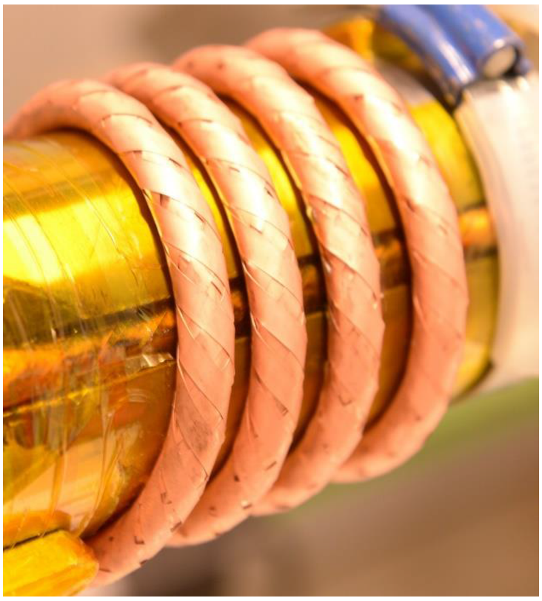

Figure 10. The sample holder including the cable, showing the strong deformation (buckling) of the tapes due to the small bending radius.

REBCO Roebel cables are considered for application in high-temperature superconducting inserts for accelerator magnets because of their fully transposed geometry, high-engineering current density, and adequate bending tolerance. In these magnets the cables experience Lorentz forces leading to transverse stresses up to 100–150 MPa. Previous reports have shown bare Roebel cables to degrade under such high stresses so that additional reinforcement is required. In this work, two identical Roebel cables are vacuum impregnated with a mixture of epoxy and fused silica in order to improve their tolerance to transverse stress. After impregnation, the critical current of the cables is measured under transverse mechanical loading at $T = 4.2$ K, $B\perp$ = B 10.5 T. A reference cable without impregnation is tested as well. Pressures up to 350 MPa are applied to a short (30 mm) section of each cable. No degradation was observed for pressures up to 250 MPa and 170 MPa in the two impregnated cables. The critical current of the nonimpregnated cable, in contrast, started to decrease at stresses as low as 40 MPa.

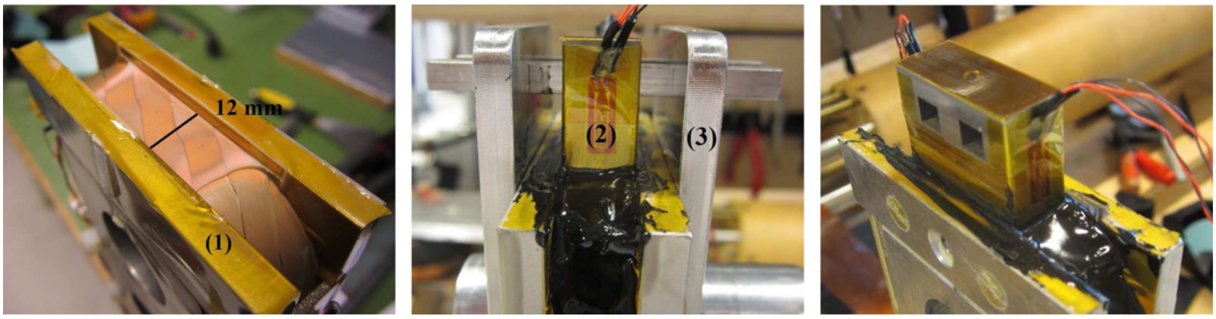

Figure 11. Cable 2 on the U-shaped sample holder. The cable is supported against the lateral Lorentz forces on both sides by side plates (1). (a) After impregnation and removal of the Teflon block. (b) The pressure anvil (2) being glued in place with Stycast epoxy. The block is aligned to the sample holder using two positioning plates (3). (c) After curing the Stycast and removal of the positioning plates.

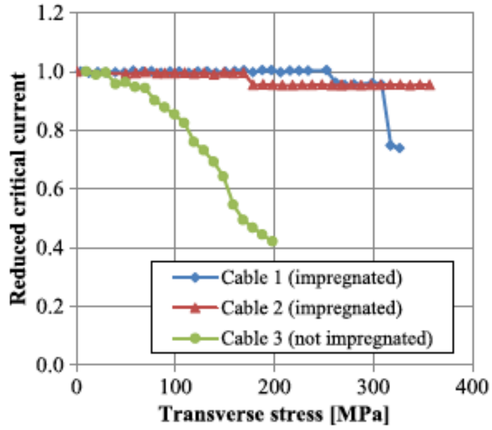

Figure 12. The critical current as a function of transverse stress. The lines connect the data points in chronological order. The critical current is normalized to the initial value for each sample.

5. Intra-strand resistance and current transfer length in multifilamentary NbTi, Nb_3Sn, MgB_2, BSSCO and REBCO conductors

The current transfer length of multi-filamentary superconducting NbTi and Nb3Sn strands was measured and analyzed. The aim is to understand and quantify the current distribution process between matrix and superconducting filaments occurring at current injection joints or shunting localized interruptions like originated by transverse cracks or high strain, temperature, or magnetic field in filaments.

An experimental setup for the measurement of the current transfer in multifilamentary wires was used to monitor the voltage profile along the strand length with a series of closely spaced thin copper potential tips (see *Figure 13*).

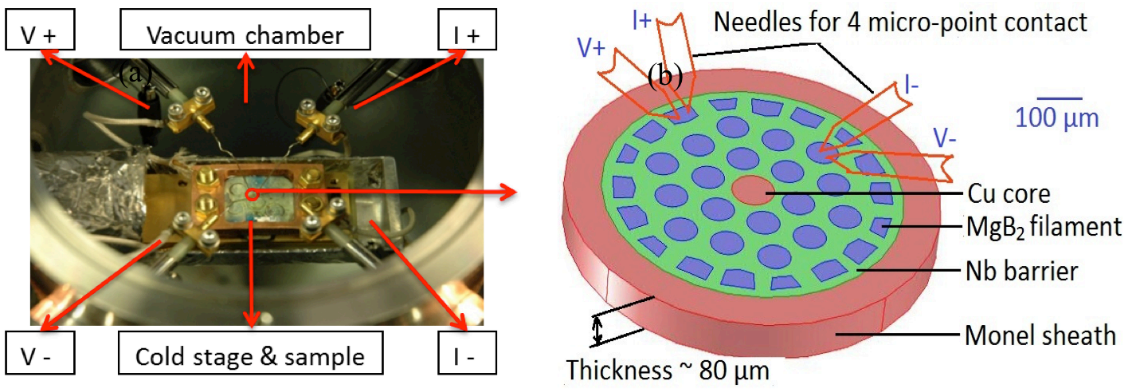

Figure 13. (a) Photograph of the Point Contact experimental setup. (b) Four point contact tungsten needles coated with gold on the top (diameters of tip and top are 8 and 0.1 µm).

The experimental results for NbTi and Nb3Sn strands are presented and analysed. The current transfer length was investigated on two different multi-filamentary Nb3Sn wires and one NbTi wire. In contradiction to available interpretations in literature, the current transfer length is not constant but increases with the distance from the current injection point. It was found that the current transfer length cannot be simply represented by a single parameter but depends on the ratio of transport current and critical current and the distance from the current injection point or local interruption of the superconducting path in the filamentary zone. With the aid of our numerical 3D

multi-filamentary strand model, simulations were performed showing excellent agreement with the experimental data.

For broader use, analytical formulae are proposed to determine the current transfer length for multi-filamentary superconductors with complex cross-sectional layout. The increasing current transfer length with the higher injected current and/or along with the distance away from the current injection point is explained by a progressive current penetration, which is caused by the high resistive matrix layers and complex layout. The progressive current penetration from the filaments in outer layers into those in the inner layers is found. That results to the increasing current transfer length measured in the experiments, which cannot be predicted by the ‘‘classical’’ current transfer model.

In addition, accurate numerical simulations were made with the numerical 3D strand model using intra-strand resistances values from direct measurements. A good match is obtained between the experimental measurements, the solutions from the new analytical model and the electrical potential distribution calculated by the numerical 3D strand model. The results have been published in a PhD thesis [P-1] and a journal paper [S-1]

6. Characterization of MgB_2 wires

For the first time, a systematic study of directly measured intra-wire resistances, AC loss and strain dependence of critical current on MgB_2 wires before and after cold high pressure densification (CHPD) have been performed and reported. Intra-wire resistance and AC loss of two Hypertech MgB_2 wires with filaments surrounded by Nb barriers have been measured and analyzed. Relatively high values of filament-to-matrix contact resistivity are found for the MgB_2 wires, being 2 or 3 orders higher than commonly found for NbTi or Nb_3Sn wires. Considering the high porosity of the MgB_2 filaments, cold high-pressure densification (CHPD) has been applied on the two MgB_2 wires to investigate its impacts on the intra-wire resistance and AC loss. The intra-wire resistance is measured with a direct four-probe voltage-current method at various temperatures (see *Figure 13*).

The AC loss is acquired by vibrating sample magnetometer (VSM) measurements at 4.2 K. Besides the intra-wire resistance measurements, the critical current of MgB_2 wires before and after densification is measured as function of axial strain with a U-shaped bending spring at 4.2 K (see *Figure 14*).

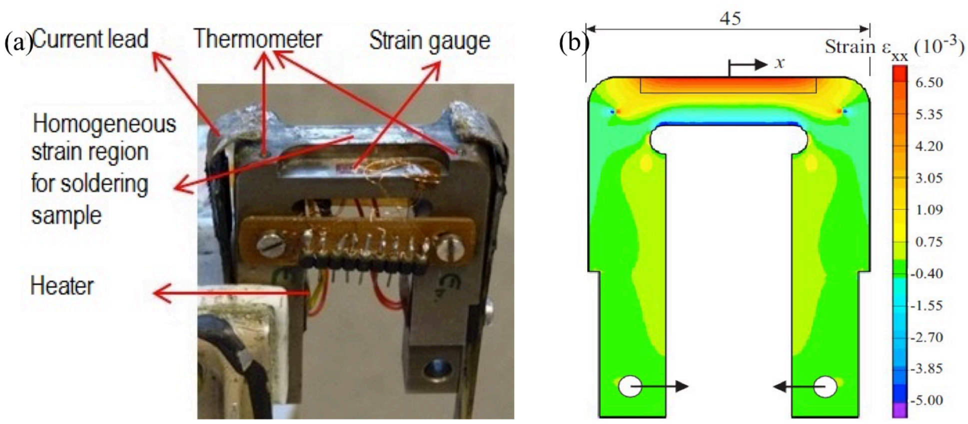

Figure 14. (a) The U-spring instrument; (b) FEM calculated strain profiles of the U-spring.

An increased critical current and AC loss, as well as a reduced intra-wire resistance are found after CHPD. The relatively high values of filament-to-matrix contact resistivity previously found in MgB2 wires, being 2 or 3 orders higher than for NbTi or Nb3Sn wires cannot be fully explained by the high porosity of the MgB2 filaments since cold high pressure densification (CHPD) resulted into only one order of magnitude decrease of the filament-to-matrix contact resistivity. For the multi-filamentary

MgB_2 wire with relatively thin barrier, the densification pressure is limited in this method, since the occurrence of broken barriers lead to MgB2 filament poisoning by the copper. The MgB_2 wire after densification also show less sensitivity to strain and a somewhat higher irreversible strain limit.
The results are reported in an international scientific journal [S-1, S-2] and on various key international conferences.

7. Development of a MgB_2 high current cabled conductor for fusion

A consortium is formed with University of Twente (Netherlands), Hypertech Inc., Columbus, OH, (USA) Ohio State University, Columbus, OH (USA), Institute for Plasma Physics, CAS ASIPP Hefei (China), Baosheng Group, Nanjing, China, Institute for Plasma Research BHAT, Gandhinagar (India), University of Wollongong, Wollongong, Australia and the US Air Force Research Laboratory, Wright Patterson AFB, OH (USA) to design, manufacture and test a full-size 50 kA class MgB2 cabled conductor as a prototype for application in the Poloidal Field Magnets of a fusion reactor. The interest of the US Air Force Research Laboratory is in the test and analysis of the strand and cable properties in a large scale cabled conductor. For this reason also the low field and low temperature properties will be investigated. The members are shown in the scheme from Figure 15 and the schematic approach of the project is illustrated in Figure 16. The details of the consortium and project are described in [CA-1] and the program is presented and discussed at [O-12, O-14, O-15, O-21].

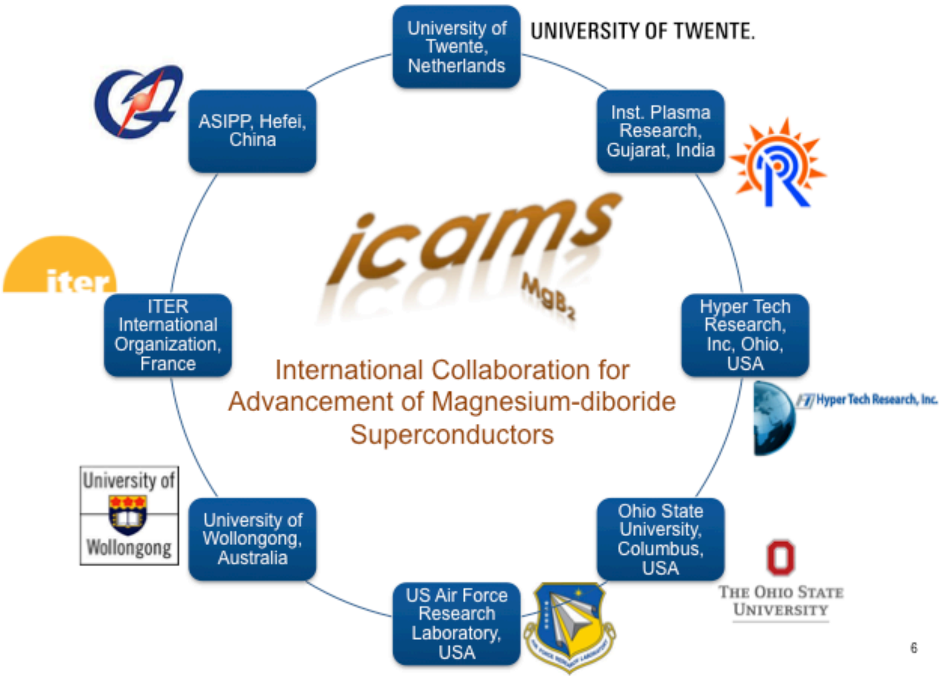

Figure 15. Consortium members of ICAMS.

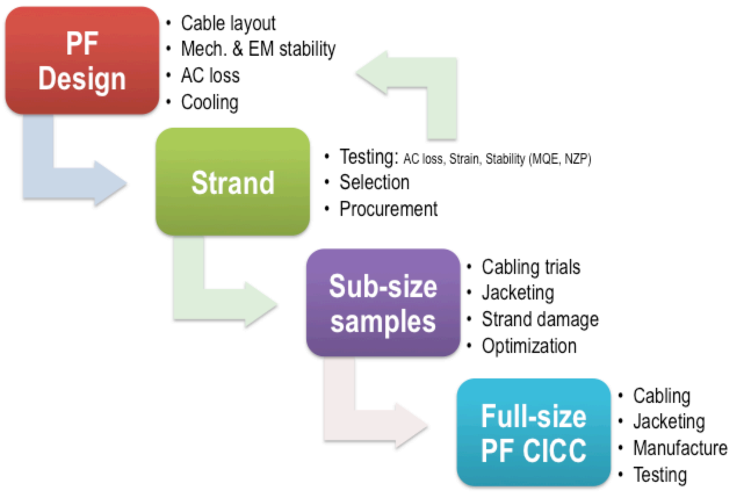

Figure 16. Schematic view of the project approach.

A start of the program is made in the meantime with Hypertech wire characterization and some results are gathered in Figure 17. The strain irreversibility limit about appears to be at least +0.3 % tensile applied strain (see Figure 18). The strain sensitivity shows about 10% Ic change from zero to - 0.4 % applied compressive strain (4.2 K and 6 T). This would reflect closely the performance reduction for the use as a CICC with steel conduit.

For the cable design, the option is to take advantage of AC Loss reduction by cable scheme optimization and implement the "close-to-one" β-ratio pitch sequence.

A first cable model JackPot analysis for an ITER 15MA plasma scenario confirms that 1G MgB_2 already could be a suitable candidate for 10 – 15 K operation in the most demanding PF coil but the goal is eventually to use 2G MgB_2 strand. So also for lower field coils (PF, CC, lower field sections of graded HF coils) and feeders it seems possible to use MgB_2 up to 20 K.

Strand #	# Mono	Barrier	Mono sheath	Multi sheath	Central fil(s)	additive	dia (mm)	% powder
3489	36	Nb	Cu	Monel	Cu	2%C	varies	11.5

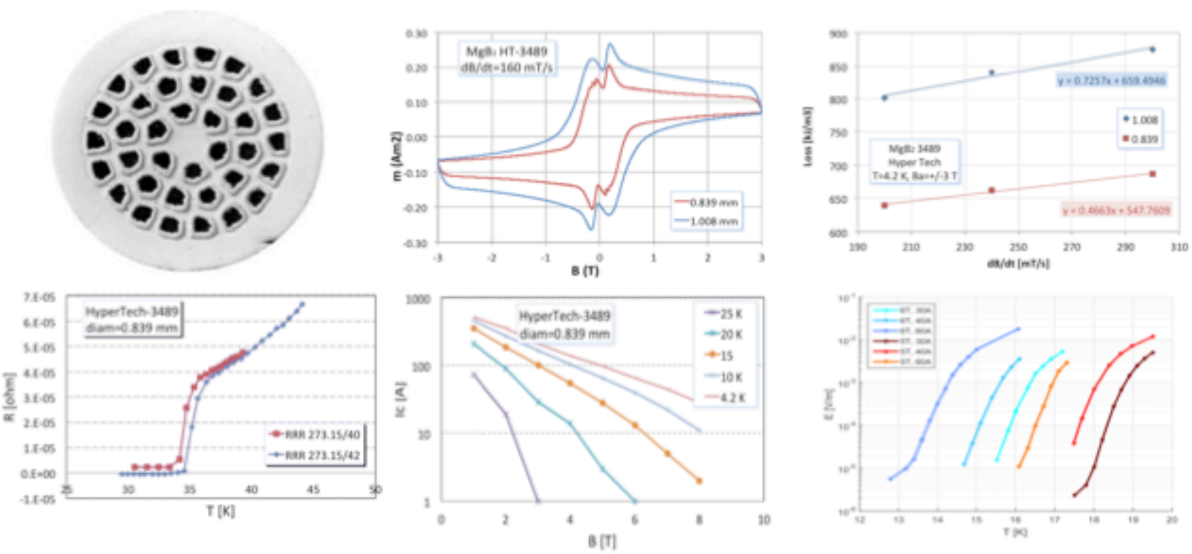

Figure 17. Summary of some first results on strand tests, e.g. magnetisation, AC loss, R(T), Ic(B,T) and E(T) measurements.

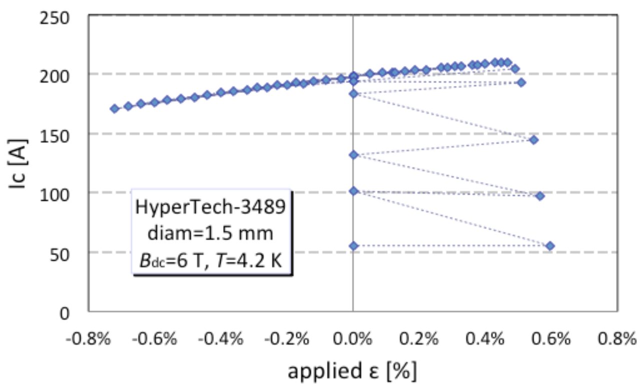

Figure 18. A result of the axial strain test showing the irreversibility limit of more than 0.4% applied tensile strain.

References

PhD thesis, Scientific journal papers, reports and presentations

P-1 C. Zhou, 'Intra Wire Resistance and Strain affecting the Transport Properties of Nb3Sn Strands in Cable-In-Conduit Conductors', PhD thesis, University of Twente, The Netherlands, ISBN: © C. Zhou, Enschede, 2014.

S-1 C Zhou, M Dhallé, H H J ten Kate and A Nijhuis, 'Current transfer length in multi-filamentary superconducting NbTi and Nb3Sn strands; experiments and models', Supercond. Sci. Technol. 27 (2014) 095014 (9pp)

S-2 C. Zhou, W. Offringa, A. Bergen, W. A. J. Wessel, H. J. G. Krooshoop, M. Dhallé, M. D. Sumption, E. W. Collings, M. Rindfleisch, M. Tomsic, H. H. J. ten Kate and A. Nijhuis' Intra-wire resistance and AC loss in multi-filamentary MgB2 wires, Supercond. Sci. Technol. 26, 2013, 025002

S-3 C. Zhou, P. Gao, H.J.G. Krooshoop, M. Dhallé, M.D. Sumption, M. Rindfleisch, M. Tomsic, M. Kulich, C. Senatore and A. Nijhuis, 'Intra-wire resistance, AC loss and strain dependence of critical current in MgB2 wires with and without cold high-pressure densification', Supercond. Sci. Technol. 27 (2014), doi:10.1088/0953-2048/27/7/075002

S-4 K. Ilin, K.A. Yagotintsev, C. Zhou, P. Gao, J. Kosse, S.J. Otten, W.A.J. Wessel, T.J. Haugan, D.C. van der Laan, A. Nijhuis, 'Experiments and FE modeling of stress-strain state in ReBCO tape under tensile, torsional and transverse load', Supercond. Sci. Technol. 28 (2015) 055006 (17pp) doi:10.1088/0953-2048/28/5/055006

S-5 K.A. Yagotintsev, P. Gao, M. Dhalle, B. Van Nugteren, T.J. Haugan, D.C. van der Laan, R. Wesche, D Uglietti, W. Goldacker, A. Kario, A. Nijhuis, "AC losses and intertape resistances in REBCO stacked tape, CORC and Roebel cables", To be published in Supercond. Sci. Technol.

S-5 S. Otten, M. Dhallé, P. Gao, W. Wessel, A. Kario, A. Kling and W. Goldacker, 'Enhancement of the transverse stress tolerance of REBCO Roebel cables by epoxy impregnation', Supercond. Sci. Technol. 28 (2015) 065014 (7pp)

International Consortium Agreement on MgB_2

CA-1 A. Nijhuis, C. Zhou, W. Yu, Q. Jinggang, S. Pradhan, M.D. Sumption, M. Tomsic, M. Rindfleisch, T.J. Haugan, M.S.A. Hossain, A. Devred, "Development of MgB2 Superconductors for Fusion Magnets; International Collaboration for Advancement of Magnesiumdiboride Superconductors", 3 May 2015

International conference presentations

O- 1 A. Nijhuis, K.A. Yagotintsev, P. Gao, J. Kosse, R. Lagraauw, S.J. Otten, M. van Melzen, R.P. Pompe van Meerdervoort, M. Dhalle, W.A.J. Wessel, H.J.G. Krooshoop, T.J. Haugan, D.C. van der Laan, F. Fabbri, G. Celentano, Mechanical loading of REBCO coated conductors, joints and CORC cables, effect on critical current and AC losses, Oral presentation EUCAS 2013, Genua, Italy, 16 September 2013

O- 2 A. Nijhuis, K.A. Yagotintsev, P. Gao, J. Kosse, R. Lagraauw, S.J. Otten, M. van Melzen, R.P. Pompe van Meerdervoort, M. Dhalle, W.A.J. Wessel, H.J.G. Krooshoop, T.J. Haugan, D.C. van der Laan, F. Fabbri, G. Celentano, Mechanical loading of REBCO coated conductors, joints and CORC cables, effect on critical current and AC losses, Oral presented at EFDA HTS Meeting, Garching bei Muenchen, Germany, 1 October 2013

O- 3 A. Nijhuis, K.A. Yagotintsev, P. Gao, J. Kosse, R. Lagraauw, S.J. Otten, M. van Melzen, R.P. Pompe van Meerdervoort, M. Dhalle, W.A.J. Wessel, H.J.G. Krooshoop, T.J. Haugan, D.C. van der Laan, F. Fabbri, G. Celentano, Mechanical loading of REBCO coated conductors, joints and cables, effect on critical current and AC losses, Oral presented at EFDA HTS Meeting, Garching bei Muenchen, Germany, 5 December 2013

O- 4 A. Nijhuis, K.A. Yagotintsev, P. Gao, J. Kosse, R. Lagraauw, S.J. Otten, M. van Melzen, R.P. Pompe van Meerdervoort, M. Dhalle, W.A.J. Wessel, H.J.G. Krooshoop, T.J. Haugan, D.C. van der Laan, F. Fabbri, G. Celentano, Mechanical loading of REBCO coated conductors, joints and cables, effect on critical current and AC losses, Oral presented at HTS4Fusion Workshop CRPP, Villigen, Switzerland, 22-23 January 2014.

O- 5 K. Ilin, K.A. Yagotintsev, C. Zhou, R. Lubkemann, T.J. Haugan, D.C. van der Laan, A. Nijhuis, "FEM Modeling of stress-strain state in REBCO tape under tensile, torsional and transverse load" 14 May 2014, HTS Modeling Workshop, IEE, Bratislava, Slovakia.

O- 6 A. Nijhuis, K. Ilin, K.A. Yagotintsev, C. Zhou, R. Lubkemann, T.J. Haugan, D.C. van der Laan, "Experiments and FEM modeling of REBCO tape and cable, Twente program 2014-2018", 27 May 2014, EUROFUSION HTS Kick Off Meeting, KIT, Karlsruhe, Germany.

O- 7 K.A. Yagotintsev, P. Gao, M. Dhalle, T.J. Haugan, D.C. van der Laan, R. Wesche, D. Ugletti, A. Nijhuis, "AC loss tests on CORC and stacked tape REBCO cables", Oral presented at ICEC-ICMC 2014, University of Twente, Enschede, Netherlands, 9 July 2014

O- 8 C. Zhou, K. Ilin, K.A. Yagotintsev, P. Gao, J. Kosse, R. Lagraauw, S.J. Otten, M. van Melzen, A. Krediet, R.P. Pompe van Meerdervoort, M. Dhalle, W.A.J. Wessel, H.J.G. Krooshoop, T.J. Haugan, D.C. van der Laan, F. Fabbri, G. Celentano, A. Nijhuis, "Transverse, axial and torsional strain tests on REBCO tapes", Oral presented at ICEC-ICMC 2014, University of Twente, Enschede, Netherlands, 10 July 2014

O- 9 A. Nijhuis, C. Zhou, K. Ilin, K.A. Yagotintsev, P. Gao, J. Kosse, R. Lagraauw, S.J. Otten, M. van Melzen, A. Krediet, R.P. Pompe van Meerdervoort, M. Dhalle, W.A.J. Wessel, H.J.G. Krooshoop, T.J. Haugan, D.C. van der Laan, "Transverse, axial and torsional strain tests on REBCO tapes", Oral presented at MRS 2015, San Fransisco, USA, 8 April 2015

O- 10 *A. Nijhuis, K.A. Yagotintsev, T.J. Haugan, D.C. van der Laan, R. Wesche, D Uglietti, L. Muzzi, G. Celentano, G. de Marzi, "Mechanical loading, AC loss and contact resistance for REBCO coated conductors", 19 June 2015, EUROFUSION HTS Kick Off Meeting, KIT, Karlsruhe, Germany.*

O- 11 *A. Nijhuis, C. Zhou, K. Ilin, K.A. Yagotintsev, P. Gao, J. Kosse, R. Lagraauw, S.J. Otten, M. van Melzen, A. Krediet, R.P. Pompe van Meerdervoort, M. Dhalle, W.A.J. Wessel, H.J.G. Krooshoop, T.J. Haugan, D.C. van der Laan, "Transverse, axial and torsional strain tests on REBCO tapes", Oral presented at CEC-ICMC 2015, Tucson, USA, 30 June 2015*

O- 12 *T. Bagni, M. Dijkstra, C. Zhou, A Devred Y. Wu, J. Qin, S. Pradhan, M.D. Sumption, M. Tomsic, M. Rindfleisch, T.J. Haugan, M.S.A. Hossain and A. Nijhuis, "Development of MgB2 conductors for low field coils and feeders in DEMO fusion energy reactors", Oral presented at CEC-ICMC 2015 Conference, Tucson, USA, 29 June 2015*

O- 13 *A. Nijhuis et. Al., "Research on LTS and HTS conductors at University of Twente", Invited Oral scheduled for the Beijing Jiaotong University, Beijing, China, 25 August 2015*

O- 14 *A. Nijhuis, T. Bagni, M. Dijkstra, C. Zhou, A Devred W. Yu, Q. Jinggang, S. Pradhan, M.D. Sumption, M. Tomsic, M. Rindfleisch, T.J. Haugan, M.S.A. Hossain, "Possible use of MgB2 CICCs for PF coils in future fusion devices", Oral scheduled for the Central Solenoid Model Coil Meeting at ASIPP, Hefei, China, 11 September 2015*

O- 15 *T. Bagni, M. Dijkstra, C. Zhou, A Devred W. Yu, Q. Jinggang, S. Pradhan, M.D. Sumption, M. Tomsic, M. Rindfleisch, T.J. Haugan, M.S.A. Hossain and A. Nijhuis, "Possible use of MgB2 CICCs for PF coils in future fusion devices", Poster scheduled for the 12th European Conference on Applied Superconductivity, Lyon, France, 8 September 2015*

O- 16 *K. Ilin, K.A. Yagotintsev, C. Zhou, Anvar, T.J. Haugan, D.C. van der Laan, A. Nijhuis, "Transverse, axial and torsional strain tests on REBCO tapes as a basis for CORC modeling", Invited Poster scheduled for the 12th European Conference on Applied Superconductivity, Lyon, France, 8 September 2015*

O- 17 *K.A. Yagotintsev, P. Gao, M. Dhalle, B. Van Nugteren, T.J. Haugan, D.C. van der Laan, R. Wesche, D Uglietti, W. Goldacker, A. Kario, A. Nijhuis, "AC losses in REBCO stacked tape, Roebel and CORC cables, influence of intertape resistances and twist pitch", Oral scheduled for the 12th European Conference on Applied Superconductivity, Lyon, France, 8 September 2015*

O- 18 *A. Nijhuis, K. Ilin, K.A. Yagotintsev, C. Zhou, Anvar, T.J. Haugan, D.C. van der Laan, "Transverse, axial and torsional strain tests on REBCO tapes as a basis for CORC modeling", Oral scheduled for the CHATS on Applied Superconductivity 2015, Bologna, Italy, 16 September 2015*

O- 19 *K.A. Yagotintsev, K. Ilin, C. Zhou, Anvar, T.J. Haugan, D.C. van der Laan, A. Nijhuis, "Transverse, axial and torsional strain tests on REBCO tapes as a basis for CORC modeling", Oral scheduled for the HTS4Fusion Conductor Workshop 2015, Pieve S. Stefano, Italy, 12 September 2015*

O- 20 *Konstantin K.A. Yagotintsev, P. Gao, M. Dhalle, B. van Nugteren, T.J. Haugan, D.C. van der Laan, R. Wesche, D Uglietti, W. Goldacker, A. Kario, A. Nijhuis, "AC losses and inter-tape resistances in REBCO stacked-tape, CORC, Roebel and HTS-CICC cables", Oral scheduled for the HTS4Fusion Conductor Workshop 2015, Pieve S. Stefano, Italy, 12 September 2015*

O- 21 *A. Nijhuis, T. Bagni, M. Dijkstra, C. Zhou, A Devred Y. Wu, J. Qin, S. Pradhan, M.D. Sumption, M. Tomsic, M. Rindfleisch, T.J. Haugan, M.S.A. Hossain, "Development of MgB2 conductors for low field coils and feeders in DEMO fusion energy reactors", Oral scheduled for the International Conference on Magnet Technology 24, Seoul, South Korea, 20 October 2015*

O- 22 *K.A. Yagotintsev, K. Ilin, C. Zhou, T.J. Haugan, D.C. van der Laan, A. Nijhuis, "Transverse, axial and torsional strain tests on REBCO tapes for CORC cable modeling", Oral scheduled for the International Conference on Magnet Technology 24, Seoul, South Korea, 20 October 2015*

O- 23 *C. Zhou, K.A. Yagotintsev, T.J. Haugan, D.C. van der Laan, A. Nijhuis, "Critical current versus axial strain tests on REBCO tapes from different manufacturers", Poster scheduled for the International Conference on Magnet Technology 24, Seoul, South Korea, 20 October 2015*

O- 24 *K.A. Yagotintsev, P. Gao, M. Dhalle, B. Van Nugteren, T.J. Haugan, D.C. van der Laan, R. Wesche, D Uglietti, W. Goldacker, A. Kario, A. Nijhuis, "AC losses and intertape resistances in REBCO stacked tape, CORC and Roebel cables", Invited Oral scheduled for the International Conference on Magnet Technology 24, Seoul, South Korea, 20 October 2015*

Reports

R-1 *T. Mulder, W.A.J. Wessel, H.H.J. ten Kate, "Test of a spiraled CORC cable in magnetic field", June 3, 2015, CERN-EDMS document*